

Changing snow and shrub conditions affect albedo with global implications

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[1] Observations suggest that shrub abundance in the Arctic is increasing owing to climate warming. We investigated the ramifications of a tundra-to-shrubland transition on winter energy exchange. At five sites in Alaska we suspended a 50-m-long cable above the vegetation and from this measured how the vegetation interacted with the snow and affected albedo. The sites defined a gradient from nearly shrub-free tundra to a woodland with a continuous shrub canopy. Where the shrubs were small, thin-stemmed, and supple, they were bent and buried by snow. Where they were tall, thick-stemmed, and stiff, the shrub canopy remained exposed all winter. Where shrubs were buried, mid-winter albedo values were high (0.85), but where they were exposed, the values were 30% lower (0.60). At these latter sites, melting began several weeks earlier but proceeded more slowly. Consequently, all sites were free of snow about the same time. Using the measurements and a solar model, we estimate that a land surface transition from shrub-free tundra to shrubland could produce a 69 to 75% increase in absorbed solar radiation during the snow-cover period, depending on latitude. This is two thirds the increase associated with a tundra-to-forest transition. When combined with measurements showing that a tundra-to-shrub transition would also produce a net increase in summer heating, our results suggest a positive feedback mechanism associated with a warming-induced increase in shrubs. To our knowledge, ours is the first study to document that shrubs could alter the winter energy balance of tundra in such a substantial way.

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1. Introduction

[2] Across the tundra of northern Alaska, western Canada, and parts of Russia the abundance of shrubs is increasing, possibly the start of a transition from tundra to shrubland [Shvartsman *et al.*, 1999; Sturm *et al.*, 2001a; Jia *et al.*, 2003; Hinzman *et al.*, 2005]. This transition could ultimately alter the land surface across a region that exceeds 4 million km² (R. Lammers, personal communication, 2002). The most likely cause of the transition is climate warming.

[3] One ramification of this land surface transition would be an alteration in the carbon budget of the Arctic. While all agree that changes in this budget would have global ramifications, there is still lively debate as to the nature of the alterations that would take place. On one hand, shrubs store carbon in woody stems that have long turnover times compared with annual roots and the leaves of graminoids.

This should produce a net increase in carbon storage. On the other hand, the Arctic contains nearly 40% of the world's soil carbon [Gorham, 1991; Schlesinger, 1977]. Manipulation experiments [Mack *et al.*, 2004] have shown that this soil pool can lose carbon even as the aboveground biomass of shrubs increases. Overall, there could be a net loss of carbon from the ecosystem [Loya and Grogan, 2004; Mack *et al.*, 2004; Bret-Harte *et al.*, 2002] despite an increase in shrubs. This issue, the balance between soil carbon and aboveground biomass, is sure to be the focus of considerable attention as the increase in arctic shrubs continues.

[4] A second ramification has garnered less attention. This is how the increase in shrub size and abundance would affect the surface energy budget. A few studies on this topic have been conducted during the growing season [McFadden *et al.*, 1998; Eugster *et al.*, 2000; Chapin *et al.*, 2000; Thompson *et al.*, 2004], but to our knowledge, there have been none in winter. Yet across the tundra regions of the north, winter lasts for 9 months of the year. Extended over this long period, even small changes in the energy balance can have a large

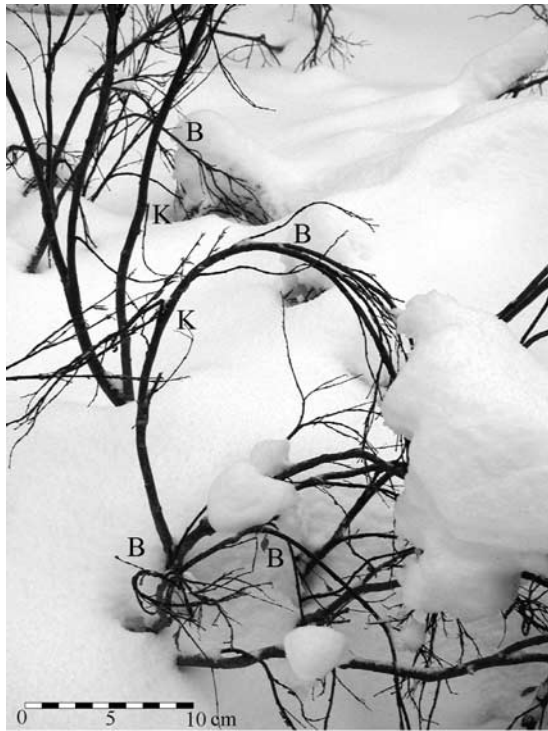


Figure 1. Early winter snow loading of shrubs (*Salix pulchra*) showing some branches that are erect, others that are bent (B) and prostrate, and still others that have been broken (K) by the weight of the snow.

cumulative impact. To quantify this effect, our study focused on the snow-cover season. We found that an increase in the abundance and size of shrubs could potentially boost winter heating by 70%. The source of this added heating is the marked contrast in the reflectivity (albedo) of snow-covered tundra compared to exposed shrubs. Shrubs are dark and absorb solar energy; snow is light and is a superb natural reflector. While previous studies have documented the general impact of vegetation on snow cover albedo [Kung *et al.*, 1964; Robinson and Kukla, 1984; Baker *et al.*, 1991], to our knowledge, our study is the first to document that increasing shrubs could have a substantial impact on the winter energy balance of tundra ecosystems.

[5] Our results are derived from a set of detailed snow and shrub measurements made at five adjacent sites in western Alaska. These sites define a gradient from tundra to forest. The gradient can also be thought of as a time trajectory for arctic land surface evolution under a warming climate [McGuire *et al.*, 2003]. At these sites we observed how the winter albedo and the spring snowmelt differed as a function of shrub size and abundance. While motivated by the tundra-to-shrubland transition, our results are applicable anywhere that shrubs invade low vegetation composed of herbaceous species, and where there is a substantial winter snow cover, for example, in alpine meadows.

2. A Conceptual Framework for Snow-Shrub Interactions

[6] Trees are tall, single-stemmed, and stiff. They are rarely laid down by snowfall and are almost never buried

because of their height. Sedges, grasses, and forbes are low and usually buried by snow. Even when they are taller than the snow, these supple plants are easily bent over and subsequently buried. Shrubs, with their multiple woody stems of varying diameter and length, exhibit a wide range of heights and stiffness. They can be buried, they can be bent over and then be buried, or they can remain erect and form a canopy above the snow (Figure 1).

[7] Two end-member states bracket the range of snow-shrub interactions.

[8] 1. Tall, stiff, erect shrubs can form a canopy above the snow. If snow clings to this canopy, it can be highly reflective, but more often it is bare of snow and therefore a good absorber of solar energy. Snow in the canopy can be shed in the space of a few hours, with rain, wind, or above-freezing temperatures determining whether the branches are loaded or unloaded. Mid-winter albedo values are unpredictable, but in the spring when consistent above-freezing temperatures cause the snow to be shed from the canopy, exposed dark branches and lower albedo values are the rule. This is also the time of year in the north when sunlight is returning after the polar night.

[9] 2. Low and/or supple shrubs can be laid down and buried by snowfall. Once buried, a low shrub landscape is visually indistinguishable from a snow-covered shrubless tundra landscape and will have the same albedo. The thickness of snow covering the branches is critical. If the layer is optically thick (estimated to be about 10 cm for average values of snow density and grain size [Baker *et al.*, 1991; Hardy *et al.*, 1998]), then the buried shrubs will have no impact on the albedo. Albedo will range from 0.7 and 0.9, similar to that of the snow cover on a glacier or sea ice [Paterson, 1981; Barry, 1996]. If the layer is optically thin, the dark branches will reduce the albedo because they can absorb solar radiation through the snow. This process will warm the branches during sunny weather and produce localized melting and chimney-like cavities (Figure 2b). In the spring, as the snow cover warms further and the bonds between snow grains weaken, the buried branches will

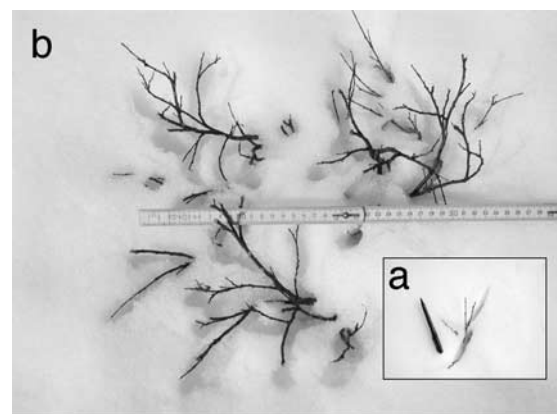


Figure 2. (a) A branch that has just popped up from warming snow with its associated melt cavity. (b) Shrub branches (*Betula nana*) that had been covered by a thin layer of snow but are now melted out due to solar heating. “Stovepipe” melt holes surrounding branches penetrate into the snow 10 to 30 cm.

Table 1. Experimental Sites, Vegetation, and Vegetation Biometrics^a

Site	Tundra	Low Shrub	Tall Shrub	Woodland	Forest
Latitude	64.5029°N	64.8917°N	64.9354°N	64.8646°N	64.9019°N
Longitude	163.6964°W	163.6496°W	163.7378°W	163.6871°W	163.6745°W
Dominant shrub canopy species	<i>Betula nana</i>	<i>Betula glandulosa</i>	<i>Salix pulchra</i> <i>Betula glandulosa</i>	<i>Salix pulchra</i>	<i>Salix pulchra</i> , <i>Salix glauca</i> , <i>Salix lanata</i>
Average shrub height, cm	20	65	110	240	100
Maximum shrub height, cm	45	120	150	300	220
Average shrub stem density, stems/m ²	<1	11	20	5	5
Maximum shrub stem density, stems/m ²	2	52	67	10	10
Average shrub stem diameter, cm	0.3	1.4	1.5	3	1.3
Maximum shrub stem diameter, cm	0.5	2.5	3.2	5.5	5
Average shrub coverage, %	<1	29	65	75	10
Maximum shrub coverage, %	5	100	100	100	75
Deciduous shrub above-ground biomass, g/m ²	46	707	1773	2012	360
Total above-ground biomass, g/m ²	582	1104	2085	3001	5208
Shrub biomass fraction	0.08	0.64	0.85	0.67	0.07

^aBiomass values from Thompson *et al.* [2004].

spring back up in a process that can reduce the albedo in an abrupt fashion (Figure 2a).

[10] We can capture some of the complex interaction of snow and shrubs using the ratio (λ) of snow depth (h_s) to shrub height (h_b),

$$\lambda = \frac{h_s(t)}{f(t) \cdot h_b}, \quad (1)$$

where t is time, and f is a compression factor that ranges from about 0.1 to 1 depending on how much the shrubs are bent over and lain down by the snow. When this ratio is applied in a climatological way where h_s is the long-term winter maximum snow depth and $f \cdot h_b$ is the mean effective winter height of a stand of shrubs several hectares in extent, it suggests three classes. For $\lambda \gg 1$ (snow-dominated), shrubs will be buried early in the winter and remain buried. For $\lambda \ll 1$ (shrub-dominated), they will remain exposed and dominate the albedo. For $\lambda \approx 1$, the outcome (buried or not) will vary from one winter to another, and can change if there is a general increase in the size of shrubs or a shift in winter precipitation. Snow-shrub systems with λ values near 1 are sensitive to change and can exhibit threshold behavior, switching from albedo values dominated by snow to ones dominated by dark vegetation.

[11] Equation (1) can also be applied to the interaction of snow and shrubs during a single winter. In this case, snow depth increases with time as the snow cover builds up, so λ changes through the season. The $f \cdot h_b$ will be a constant value if the shrubs are stiff and do not bend, but the product will undergo a rapid, step-like decrease if the shrubs are supple and lain down by the snow. This usually occurs during early winter storms, ones that deposit a substantial amount of snow. Lay-down can literally occur overnight. If the air temperature is near freezing during the storm, the snow will stick to the branches, which will then be even more likely to be heavily loaded. At the end of the storm $f \cdot h_b$ will be approximately equal to the snow depth ($\lambda \approx 1$). Subsequent snowfall will produce λ values exceeding 1 and a snow cover that, for purposes related to solar energy absorption, is effectively snow-dominated.

3. A Snow-Shrub Interaction Experiment

[12] During two winters (2000–2002), we observed the interaction of snow and shrubs near Council, Alaska

(64°53'N, 163°39'W). Council lies in a tundra-forest transition zone, so we were able to select five sites (Table 1) within 5 km of the town that defined a vegetation gradient from tundra to forest. Owing to their proximity, the sites experience similar weather and receive similar amounts of snow. With one exception (woodland), these were the same sites used during ATLAS project (Arctic Transitions in the Land Atmosphere System) [see McGuire *et al.*, 2003]. They have been described by Thompson *et al.* [2004]. Extensive data for these sites can be found at <http://www.joss.ucar.edu/atlas>. In this part of Alaska, both shrubs [Silapaswan *et al.*, 2001] and trees [Lloyd *et al.*, 2003] are expanding into tundra, apparently in response to warming.

[13] Our particular experiment consisted of measuring shrub stand structure and observing whether the shrubs at each site were lain down or remained erect as the winter snow pack accumulated. We also measured the albedo above the snow-shrub surface, recording the snow depth and rate of melt throughout the winter and spring.

3.1. Albedo Measurements

[14] At each of the sites, we installed a 50-m-long cableway from which we could measure the albedo of the underlying snow and vegetation without disturbing either (Figure 3). These cableways remained in place for the 2 years of the experiment. Albedo was measured one or two times during winter, then every few days during the snowmelt season. A trolley holding upward and downward looking pyranometers (Kipp and Zonen Model 6B; 0.3–2.8 μm spectral range) and a downward looking digital camera (Nikon Coolpix 990) was moved along the cable by means of a long (5 m) pole. Aluminum swedges were crimped on the cable every meter providing a stop against which the trolley could be accurately positioned so that measurements could be repeated in precisely the same location each time. The pyranometers were suspended with thin cable from a single point of attachment so they were self-leveling. At each swedge, after a 20-s settling period, we recorded on a Campbell 510 data logger the incoming (Q_{in}) and outgoing radiation (Q_{out}), the time, and the albedo (Q_{out}/Q_{in}), each measurement being the mean of 10 readings. Using a remote control, we also took a vertical digital image of the downward-looking pyranometer footprint. By means of a second long pole at the 10, 20, 30, and 40 m locations we placed in the image a scale and identification



Figure 3. Pre-snowmelt (May 2001) and post-snowmelt (June 2001) site pictures showing that by the end of winter, all of the shrubs had been buried at the low shrub site, most had been buried at the tall shrub site, but more than half were still exposed at the woodland site. The cableways and the trolley carrying the pyranometers and digital camera are visible in most of the pictures. The same trolley was used at each site. It was moved along the cable by means of a long pole with the instruments triggered remotely. The pole was attached to the trolley about 50 cm away from the pyranometers and did not shade or adversely affect the readings.

panel that keyed the images to the albedo readings and controlled them for scale. The cableways were aligned east to west with the operator always working on the north side in order to eliminate shadowing.

3.2. A Special Case in the Forest

[15] At the forest site, where the trees were more than 10 m tall, we had to place the cable in a narrow clearing between the trees rather than above them. Shadowing by the surrounding trees was common. Standard procedure at this site was to record for each albedo measurement whether the snow surface was in shadow and whether the upward-looking pyranometer dome was in direct sun or shaded. Readings where there was a shadow at either location were discarded. Above-canopy measurements from the same site [Thompson *et al.*, 2004] suggest a summer albedo of 0.11, similar to other boreal forests [Bonan *et al.*, 1992, 1995; Foley *et al.*, 1994; Betts and Ball, 1997]. Above-canopy winter measurements for boreal forests, summarized by Baldocchi *et al.* [2000], suggest a value of 0.11, but direct measurements from a 20-m tower at our experimental site indicate a value of 0.18 (J. Beringer, unpublished data, March 2005). We have offset all forest site readings by the amount necessary (-0.2) to force the site-averaged albedo at the end of snowmelt to converge with the known above-canopy value for the site. This produced pre-melt values that were still too high; these we adjusted back to 0.18 when we were doing our modeling.

3.3. Sun Elevation and Slope Corrections

[16] Warren [1982] found that snow albedo increases with low sun angle. For the set of 130 cableway albedo transects (each comprising 51 measurements) made during the 2-year course of the study, we have corrected the albedo values to a standard sun elevation angle of 40° (the average value observed during the measurements) using equations (1) and (2) of Melloh *et al.* [2002] which are based on the work of Marks [1988]. The average correction was -0.006 and the maximum, for a set of measurements taken in December (sun elevation at noon: 6°), was -0.022 . We did not correct for surface slope because these corrections would have been below the detection limit of our measuring system. Three of the five sites were level, the remaining two (Table 1) sloped approximately 5° to the south. Slopes of this angle would have reduced the outgoing light stream less than 1% for specularly reflected light, but because most light reflected from snow is diffuse, even this small amount is an overestimate.

3.4. Debris Samples

[17] As the snow melted, debris was exposed at the snow surface and lowered the albedo [Melloh *et al.*, 2001]. At each site, we sampled this debris multiple times during the melt season. Using a trowel, we collected the top few millimeters of snow and debris from a 30 by 30 cm wooden frame. In many cases, we collected these samples along radial lines from shrubs or trees in order to ascertain the fall-off in debris concentration with distance. The samples were weighed, melted, and then filtered through a 47-mm-diameter, 2.7- μ m pore size filter by means of a vacuum pump. The filters were air dried for 3 days, photographed, and weighed. Debris was examined to determine its color, nature, and source. From the net weight of the debris

and the sample area, we computed the surface debris concentration.

3.5. Snow Measurements

[18] Adjacent to the cableways we monitored the snow depth and the snow water equivalent (SWE). Beneath the cableways, we monitored the snow areal coverage. Twenty meters north of each cableway we installed 11 stakes that defined a 100-m-long line. A ruler attached to each stake allowed us to read the snow depth. We also probed these lines every 0.5 m using a self-recording snow-depth probe (U.S. Patent 5,864,059). Periodically, we cored the snow at 0, 25, 50, 75, and 100-m distances, then weighed the core to determine the liquid water content. Longer traverse lines ranging from 400 to 900 meters in length were also monitored at each site for snow depth. Snow density values were similar between sites, and except in the very late stages of the melt, fairly constant through time, so here we report changes in snow depth, which are proportional to the SWE. To compute the areal coverage of snow, we used the 51 digital images taken from each cableway during a visit. From these separate images, we produced a strip mosaic covering an area approximately 1.5 by 50 m. This color mosaic was converted into a binary image (snow = white = 0; branches, bare ground, and debris = black = 1) from which the snow area could be computed by dividing the white pixels by the total number of pixels. Producing the binary image required careful retouching of the photographs to remove dark shadows. A typical sequence of binary strips is shown in Figure 4.

3.6. Weather

[19] The weather was monitored at two meteorological towers (<http://www.uaf.edu/water/projects/atlas/metdata/atlasmetsitemap.htm>), and temperatures in and beneath the snow were monitored at 26 locations in and around the sites using 4 large and 22 minidata loggers [cf. Whiteman *et al.*, 2000] (<http://www.joss.ucar.edu/atlas/>; also http://nsidc.org/data/arcss_projects.html#LAI-ATLAS). In addition to air temperature, wind speed, and direction, a continuous record of snow depth was measured at one tower using a sonic distance ranger.

3.7. Vegetation Architecture

[20] During the summer, canopy shrub vegetation composition and architecture were measured beneath the cableways. Using a plumb bob, the point on the ground vertically below each swedge was determined. A 1 m \times 1 m, or 1 m \times 2 m, quadrat was centered on this point, and the number of canopy shrub stems, their heights, basal diameters, and species were recorded. Because the canopy shrub species was either birch or willow at all sites, only these upright and deciduous shrub species were counted. In addition, in winter we observed how these shrubs were loaded with snow, the weather conditions conducive to their loading, and under what conditions unloading occurred (see Figures 1 and 2).

4. Results

[21] Shrub height, percent cover, stem diameter, and biomass increased from the tundra to the woodland site (Table 1). The average canopy height increased by a factor of 12, rising from 20 cm at the tundra to 240 cm at the

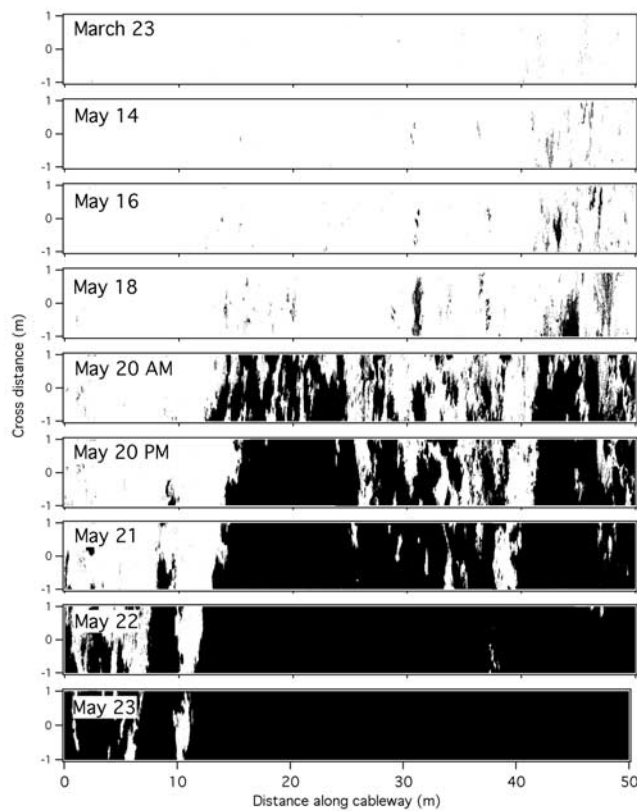


Figure 4. Binary images (white, snow; black, shrub and bare ground) of the strip of ground under the cableway at the low shrub site during the 2002 snowmelt. The strip is approximately 1.5 by 50 m.

woodland site. The canopy shrub cover also increased dramatically, rising from <1% at the tundra site to 75% at the woodland site. At the forest site, the shrub cover, which was below the tree canopy, dropped to back to 10%. Most (92%) of the total biomass at the tundra site was lichens, mosses, and evergreen shrubs [cf. *Thompson et al.*, 2004], but at the low shrub, tall shrub, and woodland sites, most of the biomass was woody shrubs. The forest site had the highest total aboveground biomass (5208 g m^{-2}) because of the trees, but the biomass at the woodland site (3001 g m^{-2}) was not that much lower, and virtually all of it was shrubs. In fact, the total biomass value reported in Table 1 comes from a woodland site used by *Thompson et al.* [2004]; the woodland site used in our study had more aboveground biomass. We estimate a total well over 4000 g m^{-2} .

[22] Shrub stem density and diameter also varied across the five sites, but not monotonically like total biomass. While the maximum shrub stem diameter increased from the tundra site to the woodland and forest sites, the stem density peaked at the tall shrub site (20 stems m^{-2}). It then decreased markedly (to about 5 stems m^{-2}) in the woodland and forest sites. Despite this decrease, the woodland site still had the highest deciduous shrub biomass because the stems at that site were conspicuously taller and thicker than anywhere else.

[23] Differences in shrub architecture produced distinct differences in the way snow and shrubs interacted. At the tundra (not shown) and low shrub sites, virtually all the

shrubs were buried (Figure 3) in both 2001 and 2002. This occurred not because the snow was as deep as the shrubs were tall (it was), but because the shrubs had been bent over by the snow. Snow excavations revealed that at both sites (and during both winters) a significant number of shrubs were nearly prostrate (f in equation (1) was 0.5 or lower). Burial had been achieved at much lower snow depths than we might have predicted from the local shrub height alone and λ values were greater than 1 well before the snow depth exceeded the summer shrub height. At the forest site, most of the shrubs were also buried in 2001 and 2002, but at this site the shrub height exceeded the snow depth by a factor of 2 or more. Laydown was essential in achieving the near-complete levels of burial that were observed. In contrast, at the woodland site, which had the tallest shrubs with the largest-diameter stems, less than half of shrubs were lain down during the winter (more below).

[24] The tall shrub and woodland sites roughly bracket the threshold between snow-dominated and shrub-dominated classes. At both sites the shrubs were tall enough (Figure 3) to be exposed even when the snow was at maximum depth (115 cm in 2001; 85 cm in 2002), and at both sites the shrub cover canopy had similar heights (Table 1). Yet just prior to snowmelt in 2001 at the tall shrub site less than 1% of the surface (as viewed vertically from above) consisted of exposed shrub, while 10 times as much was exposed at the woodland site. More telling, at the tall shrub site 2.4 stems m^{-2} were exposed above the snow prior to the melt, just 12% of the total stem density (Table 1), while at the woodland site, 2.7 stems m^{-2} were exposed, 54% of the total stem density. The critical difference between the two sites was that the thinner and more flexible stems at the tall shrub site had been bent under the snow load and the branches were down, a fact confirmed by snow pit excavation. We conclude that stem diameter is the main controlling factor in the lay-down process, with species a second factor of less importance. The 1.5- to 3-cm-diameter birch stems (*Betula glandulosa*) at the tall shrub site were more supple than the 3- to 5-cm-diameter willow (*Salix pulchra*) stems at the woodland site.

[25] Using the binary mosaics derived from the cableway images (Figure 4), we can establish a direct link between the amount of exposed shrub and the local albedo. Each mosaic was sliced into 10,000 vertical strips (the pixel resolution), and for each strip the white (snow-covered) fraction was computed (Figure 5, left axis). From the white fraction, the albedo, $\alpha(x)$, was computed from a simple linear mixing model,

$$\alpha(x) = \phi_s \alpha_s(t) + (1 - \phi_s) \alpha_b, \quad (2)$$

where x is distance along the cableway, α_s is the time-dependent albedo of snow, α_b is the summer albedo at the site (Table 2), and ϕ_s is the snow-covered fraction. On the basis of daily notes indicating snow surface conditions, α_s was set between 0.87 (new clean snow) and 0.6 (aged, wet snow [Warren, 1982]). The albedo function ($\alpha(x)$) was smoothed using 500 passes of a binomial smoothing filter [Marchand and Marmet, 1983]. This had the effect of producing a record that approximately matched the footprint size of the albedo measurements made from the cableway. The calculated and measured albedo agreed within a few

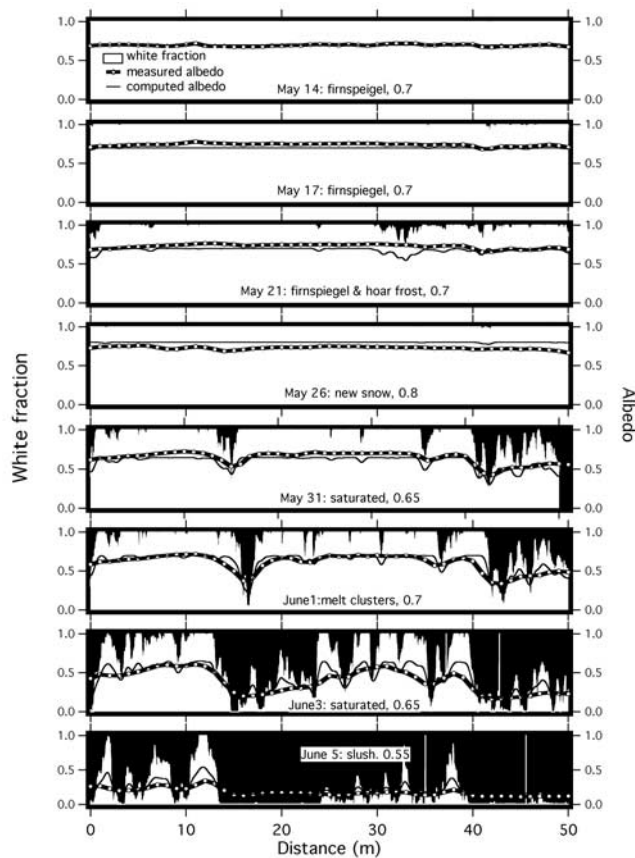


Figure 5. A comparison of measured and predicted albedo values for the low shrub site during the 2002 melt season. The white fraction, a measure of the snow-covered area, is shown on the left axis. The albedo was measured directly and also computed from the white fraction using equation (2). Albedo values for the snow were based on observed surface conditions and work by Warren [1982] (snow type and albedo value listed on each panel).

percent, and this agreement was good throughout the melt season (Figure 5). Robinson and Kukla [1984] also found that they were able to derive accurate albedo readings from black and white photographs of vegetation and snow. From their results and ours, we conclude that the local albedo was controlled in large measure by the amount of exposed shrub (not its color or nature) in the initial stages of the melt, and by the amount of exposed shrub and bare ground in the latter stages.

[26] The seasonal evolution of albedo was different at the five sites because of variations in shrub size and abundance. In April 2001, with the snow at near-maximum depth, the albedo at the tundra and low shrub sites, where all the shrubs were buried, was high (0.85; Figure 6). At the tall shrub site, with only 1% of the shrubs sticking above the

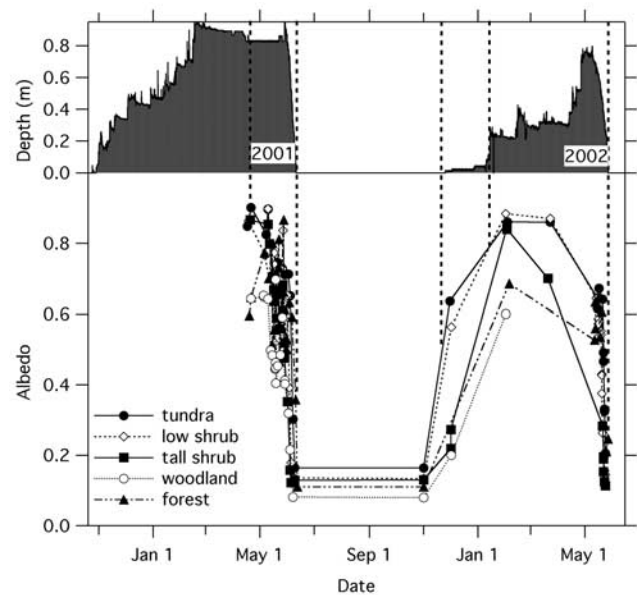


Figure 6. Seasonal evolution of (top) the snow pack and (bottom) the local albedo. The plotted values are spatial averages computed from 51 measurements taken from the cableways at each site during each visit.

snow, the albedo was equally high. At the woodland site, however, where exposed shrubs covered 10% of the area, the local albedo was 0.6, a 30% reduction. As the snow melted, the albedo at all of the sites decreased steadily, reaching summer minimums (Table 2) that ranged from 0.11 to 0.19, a fivefold reduction from winter conditions. Albedo differentiation due to shrub size was even more pronounced the following autumn. Following the first snow (6 cm), the albedo at the tundra and low shrub sites immediately increased to 0.6. At the other sites, with the shrubs still exposed above the thin snow cover, the albedo remained low. Later, when 20 cm more snow fell in one storm, it buried more than 85% of the shrubs at the tall shrub site and the albedo there immediately rose to 0.82, a value comparable to that at the tundra and low shrub sites. The same storm also produced a rise in albedo at the woodland and forest sites, but at these sites peak values (0.6) were lower. When the melt began in spring, the albedo values again dropped precipitously as the seasonal cycle was repeated.

[27] A closer look (Figure 7) at the spring albedo record shows that where there was more exposed shrub, the albedo began to decrease earlier in the melt season than where there was less shrub, but it decreased more slowly. To emphasize these trends, we have removed a few high spikes (albedo >0.80) in the record that were the result of light dustings of new snow. At the tundra site, where no shrubs were exposed, the albedo remained high almost to the end of the melt, at which time it dropped precipitously, decreasing

Table 2. End-of-Melt Albedo Values by Site

Site	Tundra	Low Shrub	Tall Shrub	Woodland	Forest
End of melt albedo, 2001	0.16	0.14	0.13	0.13	0.13
End of melt albedo, 2002	0.21	0.15	0.11	—	0.11
Values from Thompson et al. [2004]	0.19	0.17	0.15	0.13	0.10
Average	0.19	0.15	0.13	0.13	0.11

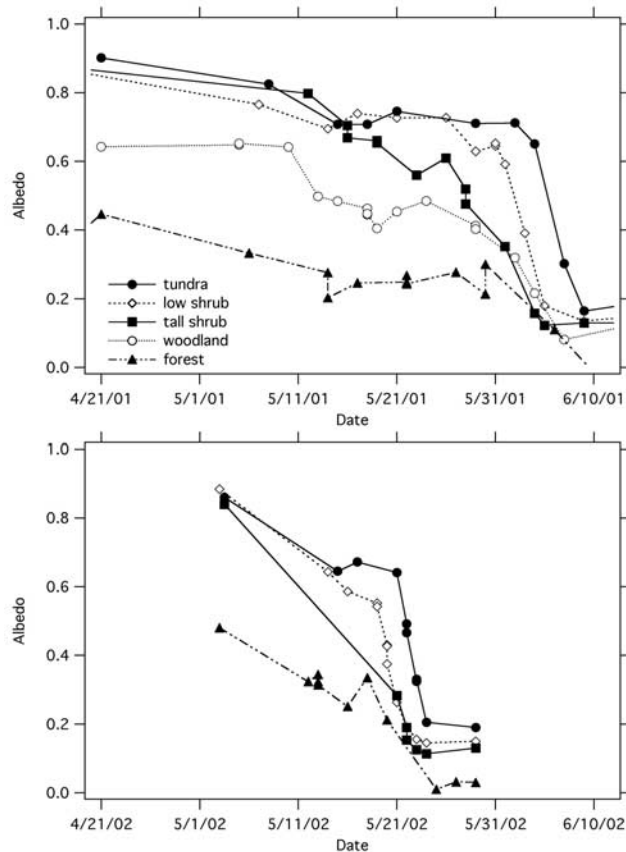


Figure 7. Evolution of local albedo at the five study sites during the melt season for (top) 2001 and (bottom) 2002. The albedo at sites with exposed shrubs (or trees) began to decay earlier in the melt period, but at rates that were lower than at sites with little or no exposed shrubs. In 2002, no measurements were available from the woodland site, but otherwise, a similar pattern was observed.

from a near-maximum value to the absolute minimum in just 6 days. At the tall shrub site, where buried shrubs became exposed early during the melt, almost a month separates the maximum and minimum values. These differences in melt duration can all be ascribed to variations in the starting date of the albedo decay, because all of the sites reached their summer minimums (Table 2) within a few days of each other.

[28] Snow melt rates also varied as a function of shrub density and site-to-site variations in albedo (Figure 8). Particularly during the early and middle stages of the melt, melt rates at the forest, woodland, and tall shrub sites, where there were exposed shrubs (or trees), increased noticeably faster than at the tundra and low shrub sites, where the snow cover was continuous and the albedo was high. This spatial pattern was pronounced in 2001 when near-freezing but sunny weather prevailed during the early and middle stages of the melt (Figure 8, top), but more subdued in 2002 when the melt was driven by air temperatures as much as 20°C above freezing (Figure 8, bottom). In 2001, as shrub branches emerged from the warming and melting snow, the melt rates between shrubby and non-shrubby sites diverged, producing the prominent fanning of the traces in Figure 8 (middle). With the arrival of above-freezing

temperatures (5° to 10°C), sensible heat transfer overtook solar heating as the primary mode of energy exchange, and the impact from lower albedo values was reduced. Once sensible heating dominated, the highest rates of melting shifted to the tundra and low shrub sites where little melting had yet taken place. In 2002, by way of contrast, it was cool and cloudy early in the melt season. Then it warmed up dramatically (air temperatures of 10 to 23°C) and these above-freezing temperatures persisted until all the snow had melted (Figure 8, bottom). The entire 2002 melt period was dominated by sensible heat exchange. Consequently, melt rates were similar at all of the sites with the exception of the tall shrub site. There, with considerably more exposed shrub than in 2001 (due to the lower mean snow depth), the albedo effect of the dark branches contributed to the accelerated melt rate.

[29] Despite noticeable amounts of debris in the snow at the sites, we found that it contributed little to the reduction in albedo, and therefore had little effect on snowmelt rates. The debris consisted primarily of leaves, sticks, and spruce needles. At the tundra site, with only a limited source for this litter, the snow was relatively clean. At the forest site,

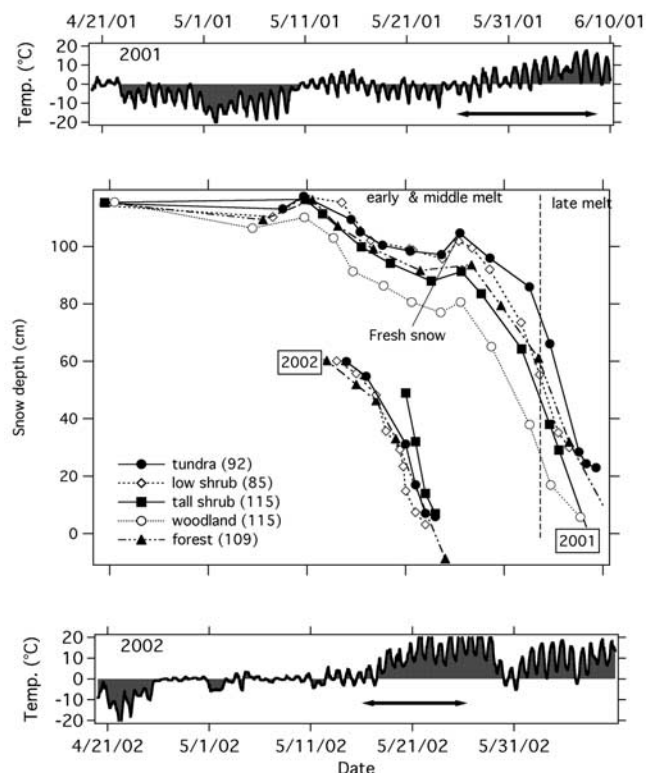


Figure 8. Snowmelt rates at the five sites (middle) for 2001 and 2002. The rates shown are averages computed from 11 stake measurements at each site. (top) In 2001, when a long period of cool but sunny weather prevailed, melt rates at those sites where shrubs were exposed (forest, woodland, and tall shrub) were distinctly higher than at those sites (low shrub and tundra) where they were not. (bottom) In 2002, air temperatures rose so rapidly and to such high levels that melting due to sensible heating dominated the melt regime and differentiation due to shrub abundance was minimal.

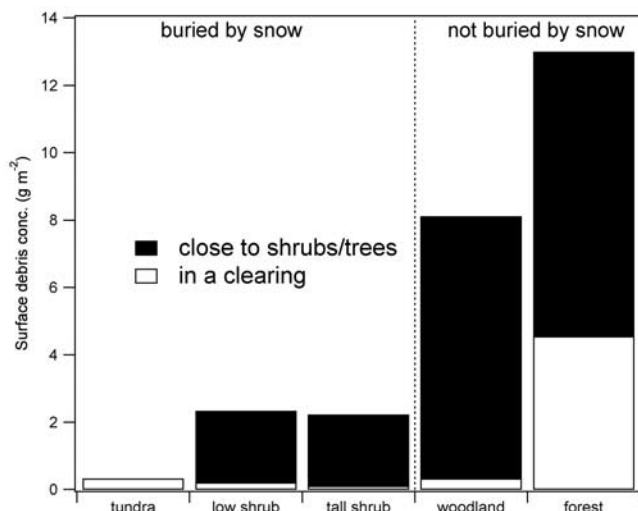


Figure 9. Surface debris loading by site. Debris was highly localized, with higher concentrations near sources (trees and shrubs). Sites where sources were buried by snow had distinctly lower concentrations than sites where sources were exposed to winds throughout the winter.

where debris concentrations were heaviest (Figure 9), the amount of debris was a strong function of distance from source trees; even small clearings contained quite clean snow. Not surprisingly, the debris concentration was also a function of whether the local shrubs were buried or not. At sites where the shrubs were buried, there was less debris because these shrubs were protected from the wind that would otherwise have stripped leaves off branches and deposited them in the snow.

[30] We estimated the maximum reduction in albedo due to surface debris ($\Delta\alpha_p$) by analyzing an image taken at the forest site late in the melt when the debris had concentrated at the snow surface. This was the dirtiest snow we observed at any of the sites. We used a modification of equation (2),

$$\Delta\alpha_p = (1 - \phi_s)[\alpha_s - \alpha_d], \quad (3)$$

where the subscripts p , s , and d indicate the albedo for the photo, the snow, and the debris load, respectively. We set α_s equal to 0.7 and α_d equal to 0.1, and used a measured value of ϕ_s equal to 0.95. This gave us a maximum reduction, $\Delta\alpha_p$, of 0.03, or 4%, an amount near the detectable limit of our measurements. In most cases, the surface debris load was much lower and the impact of debris on the albedo was considerably less.

5. Ramifications

[31] Increasing the shrub abundance in a tundra landscape affects the surface energy exchange through a simple process. Where dark shrub branches are exposed, highly reflective snow is replaced by a material with a much lower albedo. A linear mixing model (equation (2)), its only complexity being that we must allow for snow aging and grain coarsening, predicts the albedo quite accurately from the fraction of exposed shrub. Through this simple replacement process, winter surface albedos can be reduced 30% or

more (Figures 6 and 7). In principle, the reduction is effective the entire time that there is snow on the ground, but in practice, at higher latitudes in mid-winter where there is little (or no) sunlight, the effect is limited. Accordingly, in these latitudes the impact of increasing shrubs is most pronounced in spring when there is ample sunlight, a point we confirm shortly using a model. The reduction in albedo results in more solar radiation being absorbed, ultimately producing an increase in sensible heating and local warming. Our observations of accelerated melting at sites with more exposed shrubs (Figures 2 and 8) confirm this.

[32] The critical issue is whether shrubs will be exposed above the snow surface. Because shrubs can be bent over, as indicated in equation (1), the physical size of the shrubs and the depth of snow alone may not be sufficient to predict whether the shrubs are exposed. Furthermore, because shrubs are living and can grow, the interactions between snow and shrubs take place on two fundamentally different timescales: annual and decadal. On an annual timescale, the weather (the particular sequence of winter storms that produces the snow cover) is the main driver. On the decadal timescale, shrub growth can be the more important control. At both scales, the threshold condition (whether shrubs remain erect or lay down under a snow load) introduces nonlinear behavior that is currently beyond our ability to predict. During a single winter season, the threshold may be exceeded if a particular storm dumps enough snow (how much?), but over decades, exceeding the threshold is likely to be affected more by changes in shrub size, architecture, and shrub stand composition.

[33] We think it is particularly important to understand the ramifications of increased shrubs at the decadal timescale because it is at this timescale that there could be major societal impacts. There is mounting evidence [Shvartsman *et al.*, 1999; Sturm *et al.*, 2001a; Jia *et al.*, 2003; Hinzman *et al.*, 2005] that a widespread, multidecadal expansion of shrubs has been underway in the Arctic. Current estimates indicate that there are about 4 million km² of tundra in the Arctic and sub-Arctic regions (R. Lammers, personal communication, 2002), a large fraction of which could be (and in the past was [Brubaker *et al.*, 1995]) overrun with shrubs. If large expanses of arctic tundra are converted to shrubland (shrubs that are stiff and higher than the snow cover), how will the surface energy balance of the region change?

[34] To answer the question, we developed a model that combined (1) the solar cycle as function of latitude, with (2) the albedo of a surface comprised of snow and varying concentrations of dark shrub. On the basis of work by Liston *et al.* [1999], we computed the hourly solar energy flux at the Earth's surface for 1 September to 31 May (i.e., a "standard" snow season) for latitudes 50°N to 75°N in 5° increments. This is the latitudinal band in which there is tundra, shrubs, and snow. The ephemeris calculations produced a daily cycle of incoming solar radiation (Figure 10, left axis), with positive values from sunrise to sunset, and zero values at night. In these calculations, we assumed clear skies and seasonally constant atmospheric attenuation. Full cloud cover would reduce our absolute values by about half, but the relative differences would be the same. We integrated the daily solar cycle to determine the cumulative solar energy available at the surface of the snow (Figure 10, right axis). With increasing latitude, the available mid-

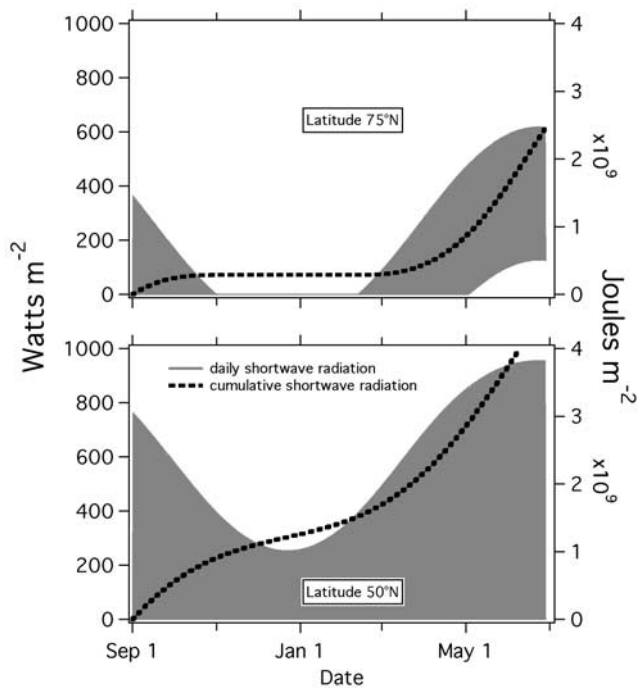


Figure 10. Daily (left axis) and cumulative (right axis) shortwave solar radiation at the Earth's surface as a function of latitude for (bottom) 50°N and (top) 75°N.

winter solar energy decreases, dropping to zero for locations north of the Arctic Circle. In spring, solar energy increases faster at these high latitude sites than it does farther south. From Figures 6 and 7, we developed standard snow season surface albedo curves for land surfaces ranging from no shrubs (shrubless tundra) to forest (Table 3). For the forest albedo curve, we assumed a winter above-canopy albedo of 0.18 and a summer value of 0.11 to match measured values from our site. We multiplied these albedo curves by the solar energy curves in Figure 10 to produce Figure 11, the cumulative winter heating as a function of shrub size and abundance.

[35] In autumn and early winter at high latitudes (75°N in Figure 11), the impact of increasing shrubs on the surface energy exchange is reduced because of limited sunlight. Not until mid-March and the return of the Sun is there any real differentiation due to shrub abundance. At that time, there is a marked increase in the amount of solar energy absorbed

by forests and woodlands. At lower latitudes (50°N in Figure 11), the differentiation begins in autumn and accumulates all through the winter and spring. At all latitudes, there is a marked acceleration in differentiation when the melt begins and shrubs become exposed, increasing the albedo contrast. The difference in total solar energy absorbed during a standard winter between shrub-free tundra (tundra) and shrubland (woodland) ranges from 6.4×10^8 (75°N) to 13.8×10^8 J m⁻² (50°N).

[36] What would happen if a land surface consisting of shrub-free tundra was to evolve into a woodland or forest over a period of several decades? In Figure 12 (data in Table 4) we plot the ratio of the total amount of solar energy absorbed per standard winter for the new land surface (low shrubs, tall shrubs, and so on) to the amount that would have been absorbed if the surface had remained shrub-free. This ratio, the solar heating factor, ranges from 1.04 for low shrub to 2.68 for forest. The tall shrub and woodland sites at Council nearly bracket the transition between snow-dominated ($\lambda \gg 1$) and shrub-dominated ($\lambda \ll 1$) classes, and Figure 12 reflects this critical transition as well. While there is only a small difference between tundra and low and tall shrub sites, there is a large difference between the tundra and the woodland sites. A transition from shrub-free tundra to a shrubland would produce an increase in winter solar heating of 69 to 75% (Table 4). This is against a background where model runs indicate the average winter solar heating for shrubless tundra is 22 (75°N) to 52 Watts m⁻² (50°N). Most significantly, the model results indicate that a tundra-to-shrubland transition (represented here by the woodland site) would produce fully two thirds as much of an increase in solar heating as that produced by a tundra-to-forest transition.

[37] What Figure 12 does not explicitly include is the time it would take for a specified land surface transition to occur. We know that a change from tundra to shrubland

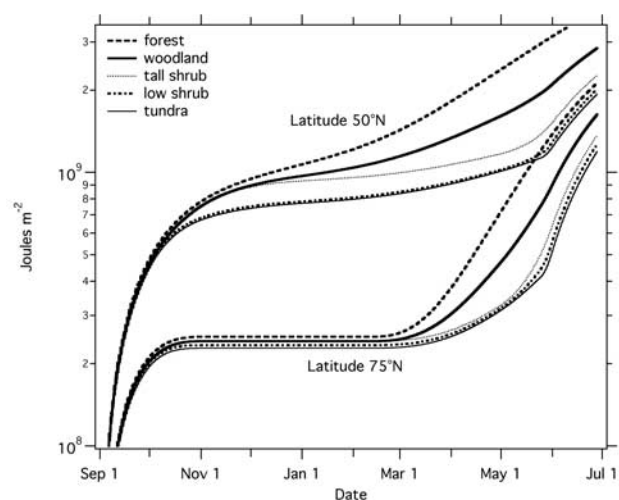


Figure 11. Cumulative shortwave solar heating for five land surfaces ranging from tundra to forest. Results highlight the differences due to the long polar night at 75°N versus year-round sunlight at 50° and indicate that differentiation by vegetation begins later in the winter at higher latitudes.

Table 3. Seasonal Evolution of Surface Albedo by Vegetation Type Based on Observed Values^a

Date	Tundra	Low Shrub	Tall Shrub	Woodland	Forest
1 September	0.19	0.15	0.13	0.13	0.11
1 October	0.19	0.15	0.13	0.13	0.14
1 November	0.60	0.60	0.20	0.20	0.18
1 January	0.85	0.85	0.85	0.60	0.18
1 May	0.85	0.85	0.85	0.60	0.18
15 May	0.82	0.78	0.68	0.49	0.18
25 May	0.72	0.63	0.45	0.36	0.15
31 May	0.20	0.16	0.13	0.13	0.11
30 June	0.19	0.15	0.13	0.13	0.11

^aValues between given dates can be computed by linear interpolation.

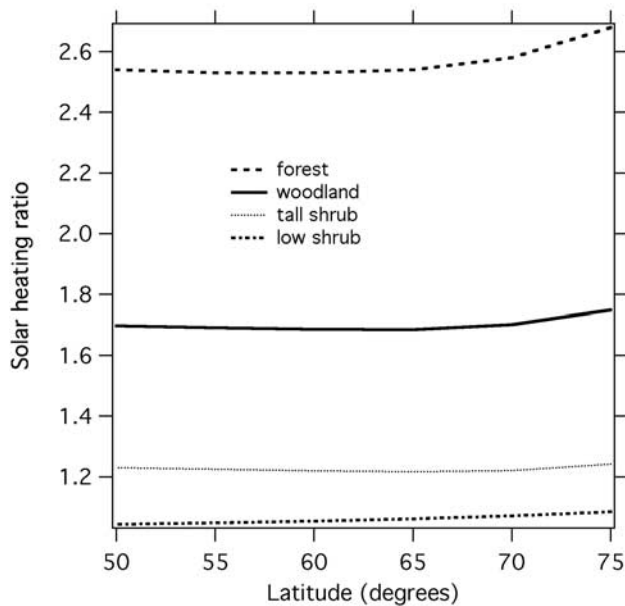


Figure 12. Solar heating factor as a function of latitude. The solar heating factor is the ratio of shortwave solar energy absorbed by one type of land surface vegetation divided by the energy that would have been absorbed if the site had been shrub-free tundra. Note that for a shrubland (our woodland site), the increase ranges from 69 to 75% (latitude 75°N and 70°N, respectively).

could occur in a few decades, while a change from tundra to forest is likely to take centuries. There are several reasons for these different rates. First, shrubs are already an important component of tundra while trees are not. Under a warming climate, the shrubs are poised to respond [Sturm *et al.*, 2001b]. Second, for physiological reasons, shrubs can take advantage of disturbance (including changes in climate) more effectively than other plant functional groups [Shaver *et al.*, 1996; Bret-Harte *et al.*, 2001]. Third, there is substantial evidence that shrubs respond positively to warming [Chapin *et al.*, 1995] while trees have a more complex response [Wilmking *et al.*, 2005]. This fast-response ability is why shrubs are commonly seen within a few years of a disturbance of the tundra by a tracked vehicle or fire [Racine *et al.*, 2004], and perhaps why there are more indications of rapid expansion of shrubs than trees in the paleo-record [Brubaker *et al.*, 1995]. Not only could a conversion from tundra to shrub-

land produce two thirds as large an increase in surface heating as a tundra-to-forest conversion, but also it could take place much more rapidly.

6. Shrub Expansion and Climate Change

[38] The sea ice-albedo feedback mechanism [cf. Maykut and Untersteiner, 1971; Kellogg, 1973] works like this: Climate warming produces a reduction in the extent and seasonal duration of sea ice. The sea ice, which has a high albedo, is replaced by open water with a low albedo. This leads to enhanced solar heating and even more loss of ice in a self-amplifying process. Increasing the abundance of shrubs in arctic tundra might produce a similar feedback effect. At least at the local level this seems to be true. Dark exposed shrubs cause local warming (Figure 2), which produces higher local rates of snowmelting (Figure 8), which in turn, exposes more shrubs, further lowering the albedo, and so on. Does this feedback effect work at larger scales?

[39] Several investigators [McFadden *et al.*, 1998; Chapin *et al.*, 2000; Eugster *et al.*, 2000; Thompson *et al.*, 2004; Beringer *et al.*, 2005] have examined the implications of a tundra-to-shrubland transition for the growing season. They concluded it would produce an increase in heating during the growing season of $\sim 10 \text{ W m}^{-2}$. For a tundra-to-forest transition, they found the increase would be about 40% larger. Albedo differences (Table 2) were one of the main drivers behind these changes, even though in summer the albedo differences are relatively small (tundra to woodland: 0.19 to 0.13, or 32%). Though there is less solar energy in winter, albedo differences are larger (Figures 6 and 7; Table 3) and they persist 3 times longer. Consequently, the potential increase in non-growing season heating is also larger, ranging from 16 to 37 W m^{-2} (Table 4, see “woodland”). They are also larger for forests, ranging from 37 to 81 W m^{-2} . Computing a weighted average from winter and growing seasons values, we estimate that the annual increase in solar heating due to a transition from tundra to shrubland would be about 20 W m^{-2} at 65°N. The value would be higher farther south and lower farther north.

[40] Lynch *et al.* [1999] and Chapin *et al.* [2000] found that allowing only for an increase in heating during the growing season, a tundra-to-shrubland transition would change the July mean air of the Arctic Slope of Alaska by $+1.5$ to $+3^\circ$. Strack *et al.* [2003] found that accounting for shrubs exposed above the snow in a winter midlatitude regional simulation led to an increase in temperature of 6°C .

Table 4. Solar Heating Ratios, and Increase in Solar Heating Due to a Transition From Shrub-Free Tundra to More Abundant Shrubs or Trees; the Last Column Provides the Computed Solar Heating Rate for Shrub-Free Tundra During a Standard Winter

Latitude	Solar Heating Ratios				Increase in Solar Heating, W m^{-2}				Tundra, W m^{-2}
	Forest	Woodland	Tall Shrub	Low Shrub	Forest	Woodland	Tall Shrub	Low Shrub	
75	2.68	1.75	1.24	1.08	37	16	5	2	22
70	2.58	1.70	1.22	1.07	42	19	6	2	26
65	2.54	1.69	1.22	1.06	49	22	7	2	32
60	2.53	1.69	1.22	1.05	59	27	8	2	39
55	2.53	1.69	1.22	1.05	70	31	10	2	45
50	2.54	1.70	1.23	1.04	81	37	12	2	52

We conclude that a 20 W m^{-2} annual increase in heating associated with the transition from shrub-free tundra to shrubland would undoubtedly produce regional warming.

[41] However, this shrub-induced warming does not ensure a self-amplifying feedback mechanism. While several studies [Chapin *et al.*, 1995; Bret-Harte *et al.*, 2001] have shown that warmer conditions favor shrub growth over other tundra functional plant groups, these results come from small-scale plot studies. What we need to understand is how the biologic aspects of snow-shrub interactions would play out at the ecosystem level. At this level, what are the ramifications if shrubs are bent over and buried by snow versus remaining upright and exposed to wind and low temperatures? Will the physiological costs and benefits of the shrubs' interactions with the snow cause communities to thrive or falter? Furthermore, as shrubs increase in abundance and size, they will alter the thermal and moisture regime of the soil, thereby altering soil microbial communities and moisture levels [cf. Sturm *et al.*, 2001b, 2005]. How will these changes impact ecosystem trajectories? Until we can answer these questions, we cannot know with certainty whether shrub expansion will result in a positive feedback to climate warming.

[42] Nevertheless, the results of our study suggest we need to monitor the ongoing increase in arctic shrubs closely while vigorously investigating whether feedback processes associated with it are significant. From other studies we know that this shrub expansion will alter the regional CO_2 budget in a profound way, and that this is likely to have an effect on the global budget. From the results presented here, along with published studies from the growing season, there is strong reason to suspect that a positive feedback mechanism for surface energy also exists. When we add these two terrestrial amplification effects to the well-known sea ice albedo feedback mechanism, and further add that as the shrubs are increasing, the sea ice is decreasing, we have good reason to think that the Arctic is going to continue warm for some time, and most probably at an accelerating rate.

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